TEMPORAL EVOLUTION OF TRADITIONAL VS. TRANSFORMED ECG-BASED INDEXES IN PATIENTS WITH INDUCED MYOCARDIAL ISCHEMIA

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by

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Abstract

The time course of changes in the ECG as a result of myocardial ischemia induced during prolonged coronary angioplasty have been studied. We have analyzed the ECG evolution during the occlusion in terms of the *Ischemic Changes Sensor* (ICS) which is a parameter that describes the capacity of different indexes to detect induced changes. Traditional indexes at specific time locations (ST level, T wave amplitude and position, and durations of QT interval and QRS complex) and global indexes (based on the Karhunen-Loève transform (KLT) as applied to the QRS complex, ST-T complex, ST segment and T wave) have been considered. The global indexes better detected ischemic changes than the traditional indexes did: the most sensitive were the index for the ST-T complex (89%) in the KLT-derived group, and for the ST level (61%) in the traditional group. Changes in the ventricular repolarization period usually appeared earlier (77% of patients) than changes in the depolarization period (23% of patients). A similar percentage of patients exhibited the earliest ischemic changes in the T wave (41%) and in the ST segment (36%). The evolution of the ICS parameters showed that the majority (60%) of the total changes occurred during the first minute of occlusion. The results suggest that the use of global ECG indexes better reflect ischemic changes than do traditional indexes, such as the ST segment deviation.

Keywords:

ECG, Ischemia, Angioplasty, Repolarization indexes, Sensitivity, Evolution.

1 INTRODUCTION

Myocardial ischemia is caused by a lack of sufficient blood flow to the contractile cells. A brief transient occlusion of a coronary artery can result in reversible ischemia, and a prolonged obstruction may lead to myocardial infarction with its severe sequellae of heart failure, arrhythmias, and death. Different ECG-based indexes have been used to diagnose myocardial ischemia and grades of ischemia have been established as an estimate of its severity. Shortly after occlusion of a coronary artery, serial grades of changes appear in the ECG: the first grade is characterized by T-wave amplitude increase (grade I), followed by ST deviation (grade II) and finally, alterations in the terminal portion of the QRS complex (grade III) [1, 2]. The clinical diagnostic and prognostic significances of these different aspects of the ventricular depolarization and repolarization periods are not still clear [3]. Ischemic ECG changes typically precede the onset of angina, and these may be the only sign of "silent myocardial ischemia" [4]. Thus it is essential to find indexes that can detect early changes in the ECG signal which may indicate the onset of an acute ischemic syndrome that may result in myocardial infarction [5].

Percutaneous Transluminal Coronary Angioplasty (PTCA) provides an excellent model to investigate the electrophysiological changes of transmural ischemia. The sudden complete coronary occlusion produced by balloon angioplasty allows the study of the initial minutes of the ischemic process that eventually would lead to acute myocardial infarction if the occlusion persisted [5]. Several studies have reported both ST segment and QRS complex changes evoked by PTCA even when the occlusion is not prolonged. Wagner et al. [6] found transient alterations of the QRS complex suggestive of conduction disturbances in patients undergoing a one to two minute elective PTCA. Kornreich et al. [5] compared additional torso and standard leads in the analysis of PTCA-induced changes both in the ST segment and the QRS complex. Changes in high frequency QRS components during PTCA have also been analyzed [7–9].

Traditionally the ECG is studied by local measurements of the waveforms, e.g. the ST-J or ST-J+60 ms points, and most indexes that quantify ischemia are related to one specific ECG point (or derived from two ECG points in the case of duration indexes), e.g. ST segment deviations [10, 11], QT variability [12, 13], repolarization alternans [14, 15], etc. Recently, global indexes based on the Karhunen-Loève transform (KLT), which reflect information contained in an entire ECG segment have been considered. The KLT has previously been used in ECG signal processing, e.g. for the purpose of ECG data compression [16–19]. In a previous work [20], the KLT was successfully applied to analyze the entire ST segment, with the specific aim of obtaining noise-tolerant methods for ischemia detection. Laguna et al. [21, 22] applied the KLT in the monitoring of the entire ST-T complex, and lately it was used to study changes in the repolarization phase during PTCA [23].

The aim of the present study is to describe the time course of ischemic changes induced during prolonged

PTCA and to determine the incidences of ischemia in the different ECG segments. The global KLT-derived indexes obtained for different ECG intervals (QRS complex, ST-T complex, ...) will be compared to traditional indexes (ST-J+60 ms level, peak T wave amplitude, etc.) for the characterization of the ischemic changes during the angioplasty.

2 MATERIALS AND METHODS

2.1 Study population and ECG acquisition

STAFF III database. The study group consists of 108 patients at the Charleston Area Medical Center in West Virginia receiving elective PTCA in one of the major coronary arteries (STAFF III study). Twenty five patients were excluded because they had ventricular tachycardia, underwent an emergency procedure or demonstrated signal loss during the acquisition. The remaining 83 patients (55 males, 28 females) were included in this study. The occlusion period was of 4' 26" in average, considerably longer than that of usual PTCA procedures because the treatment protocol included a single prolonged occlusion rather than a series of brief occlusions. The investigation conforms with the principles outlined in the Declaration of Helsinki.

The locations of the 83 dilations were: left anterior descending artery (LAD) in 27 patients, right coronary artery (RCA) in 38 patients and left circumflex artery (LCX) in 18 patients. Nine standard leads (V1-V6, I, II and III) were recorded using equipment by Siemens-Elema AB (Solna, Sweden) and digitized at a sampling rate of 1000 Hz and amplitude resolution of 0.6 μV.

Control recordings. For each patient considered in the study, the ECG recorded before angioplasty was used as a control. Therefore, we had two ECGs for each patient: the control ECG and the PTCA recording. In addition, we considered a control population of 11 normal subjects without any symptoms of cardiac diseases to estimate the normal variations of the different indexes.

2.2 Karhunen-Loève transform based indexes

The KLT is a mathematical tool which efficiently can represent the information contained in an entire signal segment by concentrating it in a few coefficients [24]. The beat-to-beat dynamic evolution of the signal can be characterized by the study of the estimated KLT coefficients evolution.

The KLT is optimal in the sense that it concentrates the signal information in the minimum number of parameters (in the mean square error (MSE) sense) [24]. Furthermore the KLT is a signal-dependent transform and needs to be derived from the statistics of the signals to be analyzed. The KLT requires that a set of basis functions (signal templates obtained for each ECG interval) has been first designed from a training set. The KLT basis functions are derived as the eigenvectors calculated for the covariance matrix of such a training set [24]. For that purpose we used a database which contains a large variety of repolarization patterns including ischemic episodes [25]. Signal pre-processing was applied in the derivation of the basis functions, including selection of beats labeled as normal according to the QRS detector and arrhythmia classificator described in [26], cubic splines baseline wander rejection [27], and correction for the effects of the HR in the repolarization period using Bazett's formula [28]. In this work, we have considered four intervals of the ECG for the detection of ischemic changes, i.e. the QRS complex, the ST segment, the T wave and the entire ST-T complex. The first order basis functions (which represent most of the signal energy [21, 22]) derived for QRS and ST-T complexes are presented in Fig. 1. Note the resemblance of the two first basis functions ($basis_0$ and $basis_1$) to QRS/ST-T complexes.

[Figure 1 about here.]

Once the KLT basis functions have been derived, the KLT coefficients can be estimated as the projection of the successive signal segments onto the basis functions (inner product). This estimation can also be done adaptively thereby improving the signal-to-noise ratio of the KLT series [22]. The KLT can be hence understood as a transformation of the ECG signal vector into a feature vector, composed by the KLT coefficients (with the first few components representing almost all the signal energy). The KLT represents globally the information of the ECG segment instead of considering only specific points of the signal as traditional indexes do, e.g. measuring ST level at 60 ms after J point. An example of KLT coefficient trends during a three minute occlusion in the LAD artery is shown in Fig. 2. The first order KLT series for the ST-T and QRS complexes (KL_0^{STT} and KL_0^{QRS}, respectively) for lead V2 are plotted and represent the morphologic changes of the ECG for each of the cardiac cycles during PTCA. The first five minutes correspond to the control recording and the next three minutes (between dash-dotted lines) to the occlusion period during PTCA. In this example it is possible to see that the first KLT index for the ST-T complex (KL_0^{STT}) shows a clear tendency of change after the first 30 seconds of occlusion, while the corresponding KLT index for the QRS complex (KL_0^{QRS}) only presents smaller variations which occur later in time. Different morphologies of both complexes (QRS and ST-T) representative of the different stages in the procedure are shown to help in the understanding of the series evolution. These trends demonstrate the relation between the changes in the KLT indexes (KL_0^{STT} and KL_0^{QRS}), and changes in ST segment, T wave and QRS complex.

[Figure 2 about here.]

In previous studies [20–23] it was demonstrated that even with a few KLT coefficients series it is possible to track the evolution of the represented signal. In this study we used 4 KLT coefficients series

(KL_i, $i = 0, ..., 3$) for each analyzed segment and then we selected that one which exhibited the largest changes.

2.3 Traditional indexes

We considered several indexes measured on specific ECG points (or derived from two ECG points in the case of intervals durations) that are traditionally used in clinical diagnosis, e.g. the level of the ST segment, the maximum amplitude of the T wave and its corresponding time location (the RTm distance), the durations of the QRS complex and the QT interval.

The ECG signal was pre-processed before performing the different measurements in the same way as described previously for the KLT indexes. Signal averaging was applied to improve the noise level of the ECG [29]. The onset and offset of the different waveforms were detected by using the automated detector of waveform boundaries described by Laguna et al. [30] and validated with cardiologists' measurements [31]. The traditional indexes were measured in each beat using the points given by the detector, and the corresponding beat-to-beat series of the indexes were obtained, i.e., a value for each beat for STJ+60 ms ($ST60$), T wave amplitude (T_a), T wave position with respect to the QRS (T_p), QRS duration (QRS_d) and QT interval length (QT).

2.4 The *Ischemic Changes Sensor* (ICS)

We want to sense the capacity of these various traditional and KLT-derived indexes to detect ischemic-induced changes. Since a comparison of these different indexes requires analysis of the changes in the context of the normal variations of the indexes, we introduced the *Ischemic Changes Sensor* (ICS). This is a parameter which reflects the capacity of a certain index to detect the ischemic changes beyond background noise level [23]. The ICS is defined by

$$ICS\ of\ the\, index:\ ICS_{index} = \frac{Amplitude\ of\ ischemic\, changes}{Normal\ variations} = \frac{\Delta index}{\sigma_{index}} \tag{1}$$

where $\Delta index$ is the amplitude of the ischemic changes reflected in the index during a PTCA occlusion (estimated by fitting a linear polynomial), σ_{index} is the standard deviation of the index as measured in the control ECG (and reflects the normal variations of the index when no occlusion is present), and *index* is any of the indexes in Tab. 1.

To study the evolution of the indexes and thus the time course of the ischemic changes, the ICS was estimated for each index every ten seconds from the beginning of the occlusion during the PTCA procedure.

An example which describes how the ICS is obtained is shown in Fig. 3 (the example is done for the $ST60$ index). A value of ICS_{ST60}= 10 found at the end of the occlusion means that the ST60 level has increased its amplitude during the occlusion 10 times its normal variations during the control recording. In the lower panel, the ICS estimated every ten seconds (measuring the changes of the index $\Delta ST60_i$, up to each instant t_i) along PTCA is shown.

[Figure 3 about here.]

To define a decision rule that shows when significant repolarization changes have been detected, we applied a threshold η to the ICS parameter. When the ICS (in absolute value) exceeded the threshold ($|ICS| > \eta$) we considered a change to be detected. This threshold was selected by measuring the ICS values of the indexes in the normal subjects set. In each subject we selected two ECG recordings: the first one to estimate the normal variations and the second one to estimate the ICS of the different indexes. The values of ICS were not larger than 2.5 in any case, and a safety rule would recommend a larger value to consider significant changes. Thus the threshold was experimentally fixed to $\eta = 8$.

By means of the ICS we compared various indexes to determine which presents an early response to the repolarization changes. For the KLT-derived indexes we selected in each segment and patient the coefficient (among the first four) that yielded the largest ICS value. Although the selected coefficient is the first one for most patients, the variety of shapes of the changes sometimes implies that they are better reflected in coefficients of higher order. We obtained trends for the different indexes evaluated along the entire procedure (before and during PTCA) and estimated the corresponding ICS during PTCA every ten seconds from the beginning of the occlusion. The results of the ICS at the end of the occlusion, the study of time courses of the different changes, and the incidences of ischemia in the different segments of the ECG are presented below.

[Table 1 about here.]

3 RESULTS

3.1 Changes at the end of the occlusion.

The KLT-derived indexes were more sensitive to the changes than were the traditional indexes showing the largest ICS values at the end of the occlusion. This is obvious from Figs. 4(a) and 4(b), where the results of the mean of the ICS (in absolute value) among the 83 patients ($mean(|ICS|)$) for the traditional and KLT-derived indexes at the end of the occlusion are represented. The ICS of the KLT-derived indexes showed larger values than those corresponding to the traditional indexes. Only the values of ICS_{ST} approached to the range of the KLT-derived ones making the $ST60$ index the most sensitive of the traditional indexes. The index corresponding to T wave amplitude (T_a) was quite sensitive showing the second largest values in its ICS values among the traditional indexes. The indexes QRS_d and T_p showed smaller ICS values and QT the smallest. With respect to the KLT-derived indexes, the KLT indexes for ST-T complex and ST segment (KL^{STT} and KL^{ST}, respectively) were those that showed the largest ICS values. The leads V2, V3 and V4 (with largest values of $mean(|ICS|)$), were the most sensitive leads for detection of induced ischemia.

[Figure 4 about here.]

3.2 Time course of changes.

We studied the timing of changes in the different indexes by calculating the evolution of the ICS during occlusion (every ten seconds from the beginning of the occlusion). We considered a change to be detected when the ICS exceeded a value of $\eta = 8$.

The KLT-derived indexes were associated with higher sensitivity than the traditional ones and yielded an earlier detection of the changes. Their corresponding ICS values exceeded the fixed threshold ($\eta = 8$) in more patients than for the traditional indexes. In Fig. 5(a), for each group of indexes (traditional and KLT-derived) are presented the results of the index that showed the best performance (KL^{STT} among the KLT-derived indexes and $ST60$ among the traditional indexes). The mean among the 12 leads for the ICS parameter of the traditional indexes exceeded the threshold in 61% of patients whereas for the KLT-derived indexes the threshold was crossed in 89%. The ICS of the KLT-derived index (KL^{STT}) exceeded the threshold earlier than did the corresponding traditional index ($ST60$) (54 vs. 61 seconds in mean after the beginning of the occlusion, respectively), although the differences in time were small as can be seen in the Fig. 5(b).

[Figure 5 about here.]

Now we present the results of the ICS evolution for the different indexes. From the first seconds of occlusion the KLT-derived indexes showed larger ICS values implying a faster response to the induced ischemia. This can be seen in Fig. 6(a) where the evolution of different ICS averaged for the 83 patients in lead V2 during five minutes of occlusion is presented. Only the ICS corresponding to the $ST60$ index reached values over 20 (approaching the values of the KLT-derived indexes). In general, QT and QRS_d indexes did not show marked changes in their mean values. During the first minute of occlusion, ICS_{ST60} and ICS_{T_a} exceeded a KLT-derived index (KL^{QRS}), indicating that changes in the QRS complex were delayed with respect to changes in the ST-T complex. However, after one minute of occlusion, QRS changes in KL^{QRS} were more noticeable than ST level changes. In leads with usual low amplitude ST-T complexes, e.g. V1 and V6, the ICS of KL^{STT} and KL^{ST} indexes had considerably lower values (see

Fig. 6(b)) than leads with usual larger amplitude ST-T complexes had, i.e. V2 (Fig. 6(a)) and V3. In such cases KL^{QRS} and KL^{STT} had similar ICS values and the traditional indexes were always below the global ones.

[Figure 6 about here.]

The ICS related to the ST-T complex were activated earlier in time than those related to the QRS complex. The first minute contained, in average for all the indexes, the largest magnitudes of change: more than 60% of the final ICS value reached at the end of occlusion. During the second minute only 16% of the maximum ICS is contributed, and during the third minute the contribution to the final ICS value is even smaller (5%). It was only in the $ICS_{KL^{QRS}}$ that relatively large changes occurred during the second and the following minutes of occlusion. The percentages accounted for the final $ICS_{KL^{QRS}}$ value along the first three minutes were 44%, 35% and 17%, respectively, while for the $ICS_{KL^{STT}}$ the percentages accounted were 59%, 20% and 6%. This result supports the observation of a delayed response of the QRS with respect to the ST-T complex during induced ischemia.

3.3 Incidences of ischemia on the different ECG segments.

We also studied the incidence of ischemia on different waveforms of the ECG (QRS complex, ST segment and T wave) to determine in which the earliest response occurred. Again we found that the indexes related to the repolarization period showed changes earlier than those related to the depolarization. Analyzing in more detail the repolarization period we found that approximately the same percentage of patients had their earliest ischemic change in the T wave and in the ST segment. To compare the timing of changes in QRS complex, ST segment and T wave we estimated the corresponding KLT-derived indexes and ICS during the occlusion. In Fig. 7(a) the percentage of patients in which the different ICS detected the earliest induced changes are shown. The indexes related to the ST-T complex were activated earlier (77% of patients) than those related to the QRS complex ($ICS_{KL^{QRS}}$ in 23% of patients). A similar percentage of patients showed the earliest ischemic changes in T wave ($ICS_{KL^{T}}$ in 41%) and in ST segment ($ICS_{KL^{ST}}$ in 36%). Again leads V1 and V6 had a larger percentage of patients with their earliest changes in the QRS complex as result of the lower projection of the ST-T complex on these leads that may be less suitable for ischemia detection. We also used the traditional indexes to study the incidence of the ischemia on the different ECG segments finding similar results (see Fig. 7(b)). The ST level (ICS_{ST60}) was activated earlier in 33% of patients, while the T wave in 36% (11% due to T wave maximum position changes (ICS_{T_p}) and 25% due to amplitude changes (ICS_{T_a})) in a similar ratio to the results found using the KLT indexes. The QRS duration index (ICS_{QRS_d}) only exceeded the threshold earlier in 9% of patients and the QT index (ICS_{QT}) in 6%.

[Figure 7 about here.]

4 DISCUSSION

It has been shown that the KLT-derived indexes better represent changes in the ECG than traditional indexes do: they resulted to be more sensitive, and also presented an earlier response to induced ischemia. This result indicates that ischemic changes appear not only in a single fixed point of the ECG but in ECG regions related to the myocardium area where the lack of oxygen is present. Thus ECG global measurements are best suited to represent changes that are reflected in signal intervals, and the KLT-derived indexes provide much more information than isolated measurements of the ECG. The use of the $ST60$ index alone is not sufficient to describe all of the ECG changes associated with ischemia.

Furthermore, it was found that traditional indexes as QT and QRS_d did not change significantly during the occlusion with respect to their normal variability in the control recordings. These indexes hence may not be very suitable to use for ischemia detection. The local indexes related to T wave (amplitude and position) and ST level showed a larger capability to detect changes. Changes in T wave position may correlate to the heart rate in some cases but the fact that the QT interval showed small ICS values (no significant changes with respect to normal variations) indicates that most T wave changes were intrinsic changes in morphology. It is relevant that morphological changes of the T wave seemed to be also more pertinent than QT duration changes.

The results of this study can be characterized in the contexts of both generally accepted knowledge and the "Ischemic cascade" of Sclarovsky et al [4]. QT interval displacements and ST segment deviations constitute the accepted "signature" of an acute complete coronary occlusion. ST segment deviations reflected in $ST60$ index occurred in 61% of the patients while KL^{STT} index revealed changes in the entire ST-T complex in 89% of the patients. These changes typically occurred within first minute of occlusion (60% of the total change was found), and then attained a lower increase. These results emphasize both the sensitivity and its inverse, the false negative incidence, of injury current development. Clinical use of KL^{STT} index might appropriately identify patients presenting with acute chest pain who are "missed" by standard electrocardiography, and therefore denied potentially beneficial reperfusion therapy [32]. The stability of both standard $ST60$ and KL^{STT} indices after only two minutes of transmural ischemia, that remains relatively constant despite ischemia so intense that depolarization is altered, may have important clinical relevance. There has been much uncertainty about the use of quantitative ST segment intervals to indicate the extent and severity of acutely jeopardized myocardium [33]. Aldrich et al [34] and Wilkins et al [35] have documented sufficient stability of the amount of ST segment deviation to merit clinical application of standard ECG indices. Results of the present study confirm this stability but suggest that use of a KL^{STT} index might provide even greater clinical utility.

The use of global indexes allowed us to study how the ischemic changes were reflected on the different ECG intervals (QRS complex, ST segment, T wave), and how they evolve during the occlusion. We found that ECG changes appear significantly earlier in the repolarization period (grade II) than in the depolarization period (grade III), emphasizing the greater vulnerability of the repolarization process to the effects of ischemia. The temporal delays between stage progression validate the concept of Sclarovsky et al [4] that these grades are ECG manifestations of three different myocardial effects of acute ischemia. However, the expected sequence of the T wave changes of grade I preceding the ST segment changes of grade II was not confirmed in the present study. Indeed there were similar values of T wave changes preceding other variations (41%), and ST segment deviations preceding other changes (36%). Furthermore these results may show the concept of Sclarovsky et al [4] that the isolated T wave abnormality of grade I indicates a higher level of myocardial protection, and the clinical study of Hochrein et al [36] that patients presenting with "hyperacute T waves" have improved outcome following reperfusion therapy.

In this work we have approached the need of a reference or "normal" value by estimating a patient-dependent reference value from the control recording. With the technique described here and the new proposed indexes we are therefore restricted to detect deviations from the reference value. This fact needs to be considered if the KLT-derived indexes (with their high level of sensitivity) are used in myocardial ischemia detection [37]. In a real situation what should be done is to estimate the reference values from an ECG interval selected during non-ischemic condition, maybe with the assessment of the clinician, and then apply the method to detect changes on the KLT coefficients (this methodology could be quite common when there are no absolute reference values to compare with: for ST level a zero value should be the normal reference, but for e.g. T wave maximum amplitude there could be a range of valid values).

The results suggest that a high percentage of patients showed QRS complex changes. It should be noted that changes detected in the QRS by the KLT-derived index (KL^{QRS}) in some cases could be secondary changes, i.e. deformations induced by ST changes on the terminal part of the QRS that is also included in the QRS window to estimate the index. Such changes were easier to find in the advanced stages of the occlusion and should be interpreted with care.

The analysis of the PTCA-induced changes on the different leads depending on the occluded vessel are not included because it was considered a topic beyond the scope of this paper. This analysis has been done in a parallel study in which the different indexes (KLT-derived and traditional indexes) are used to discriminate or identify the occluded arteries [38]. It is remarkable that the KLT-derived indexes measured on the different leads permitted a better identification or discrimination of the occluded arteries than the traditional indexes did.

5 CONCLUSIONS

The time course of the ischemic induced changes have been analyzed by means of the evolution study along the angioplasty procedure of an *Ischemic Changes Sensor* (ICS) estimated for different indexes. We have shown that the KLT-derived indexes (applied to different regions of the ECG: QRS complex, ST-T complex, ST segment and T wave) can better detect ischemic changes than the traditional indexes measured at specific locations (ST level, T maximum amplitude and position, QT interval and QRS duration). The most sensitive indexes were KL^{STT} (89% of all patients were detected) in the KLT-derived group, and $ST60$ (61%) in the traditional indexes group. The traditional indexes QT and QRS_d did not show important changes during the occlusion and those related to T wave (amplitude and position) were more significant but below the level of the ST segment. It has been shown that changes in the ventricular repolarization period usually appeared earlier (77% of patients) than changes in the depolarization period did (23% of patients). Similar percentage of patients showed their earliest ischemic changes in T wave (ICS_{KL^T} in 41%) and in ST segment ($ICS_{KL^{ST}}$ in 36%). The evolution of the ICS also showed that the main changes appeared during the first minute of occlusion (60% of the final value was reached).

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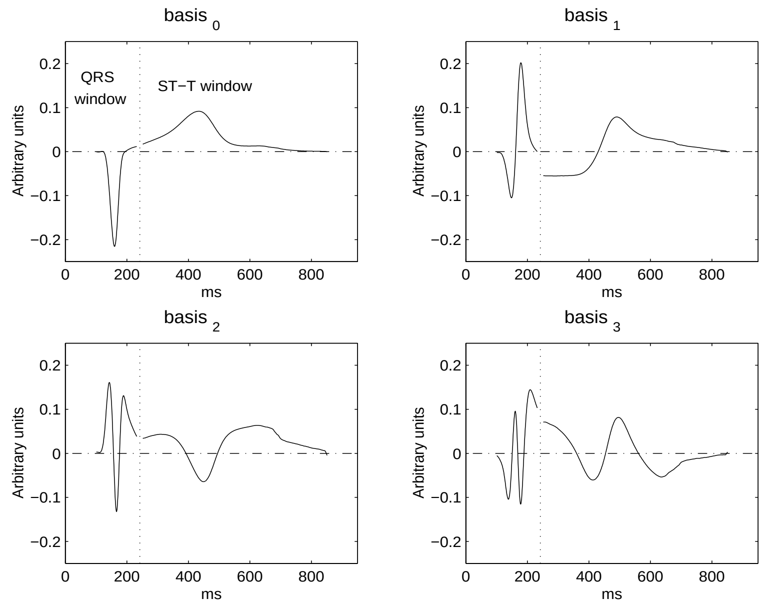


Figure 1: *First four KLT basis functions ($basis_0$, $basis_1$, $basis_2$ and $basis_3$) of QRS and ST-T complexes used in the derivation of the global indexes. Basis functions windows are referred to QRS fiducial point.*

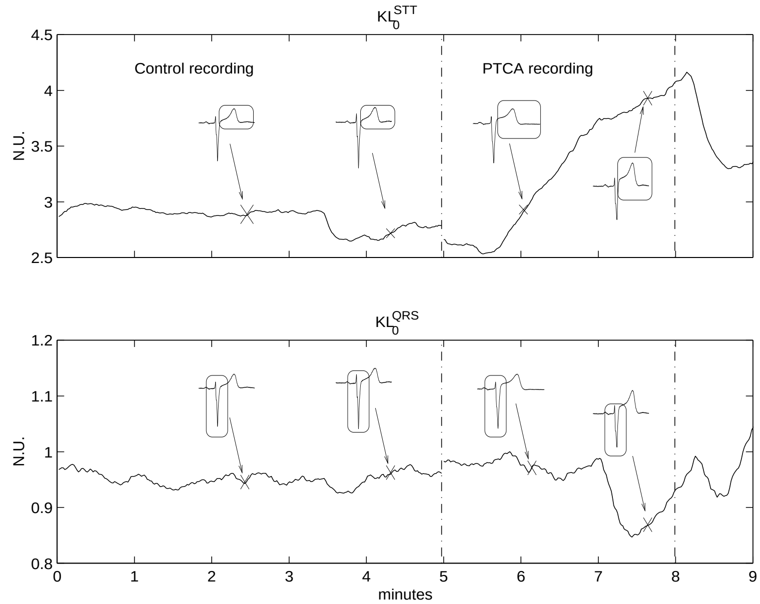


Figure 2: *The first order KLT time series for the ST-T and QRS complexes (KL_0^{STT} and KL_0^{QRS}, respectively) during a complete PTCA procedure in LAD artery (first dotted line corresponds to inflation onset and second one to balloon deflation). The series correspond to lead V2 and are expressed in normalized units. Different morphologies of both complexes (QRS and ST-T) representative of the different stages in the procedure are also shown.*

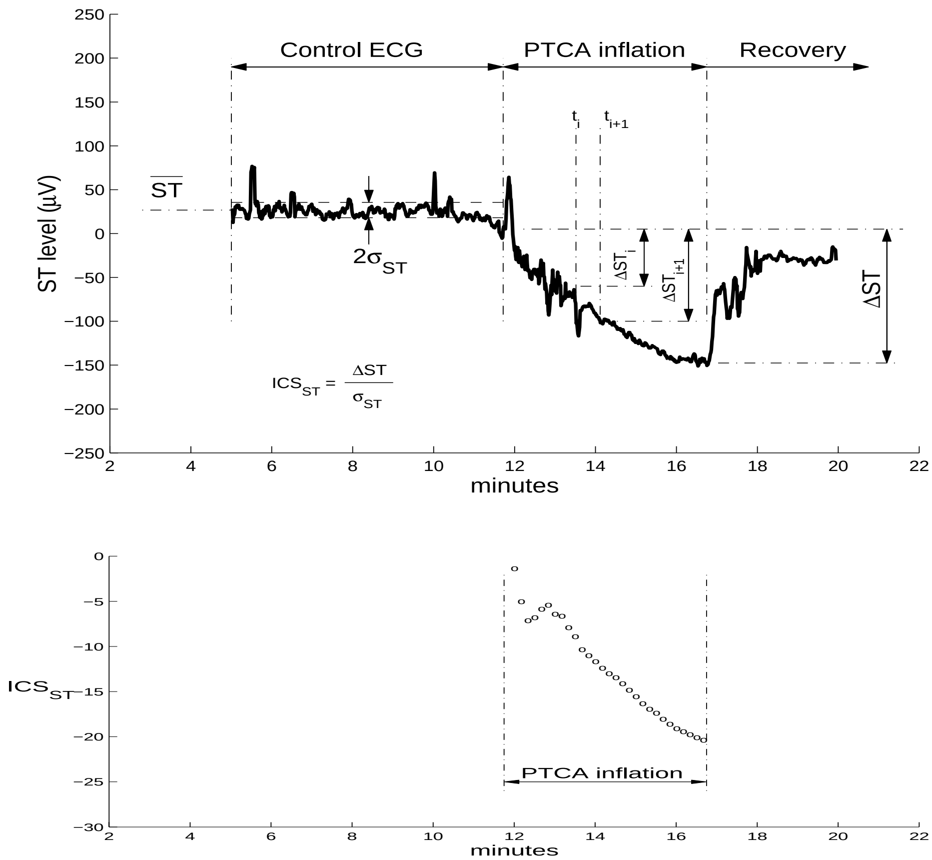
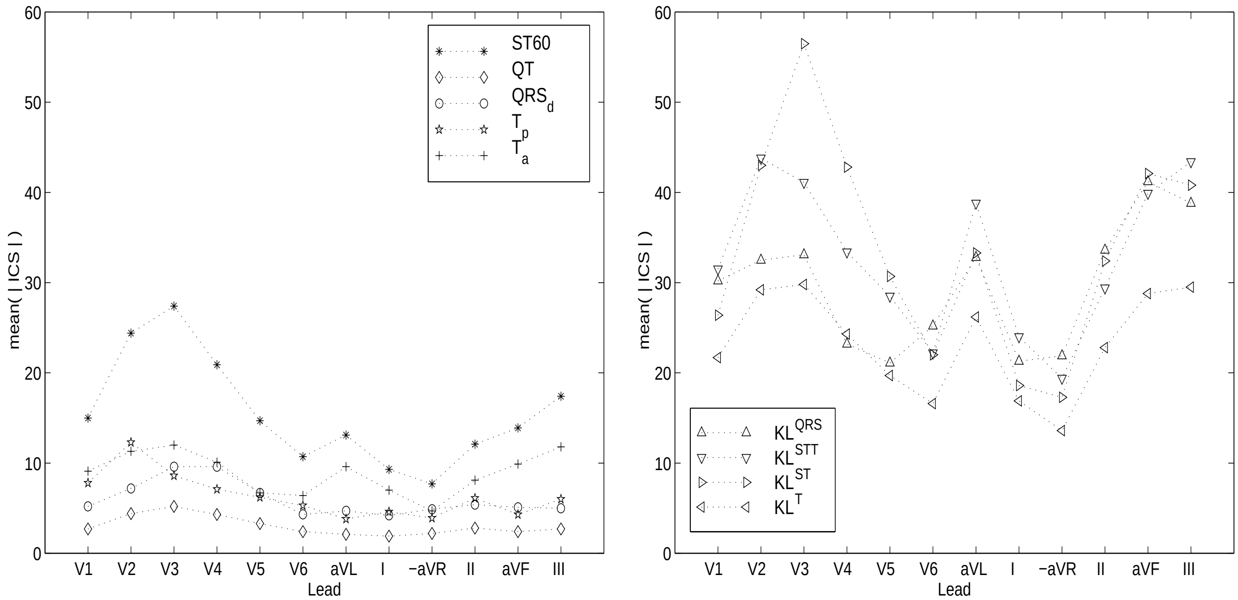


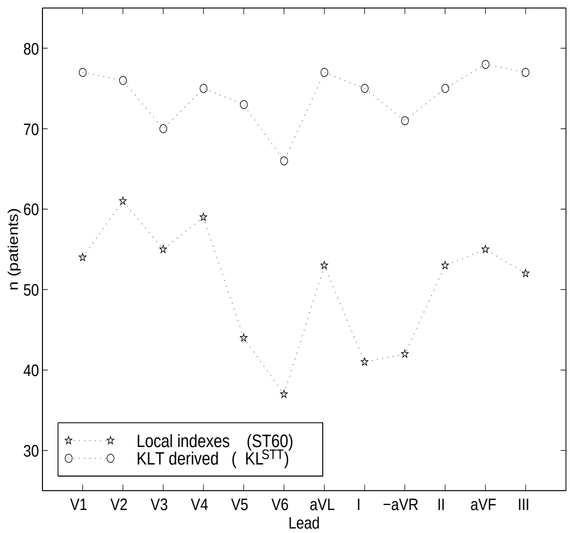
Figure 3: *Example of series evolution corresponding to ST level index (ST60) during the complete procedure (above) and derivation of the ICS of ST60 index every ten seconds during occlusion (below).*



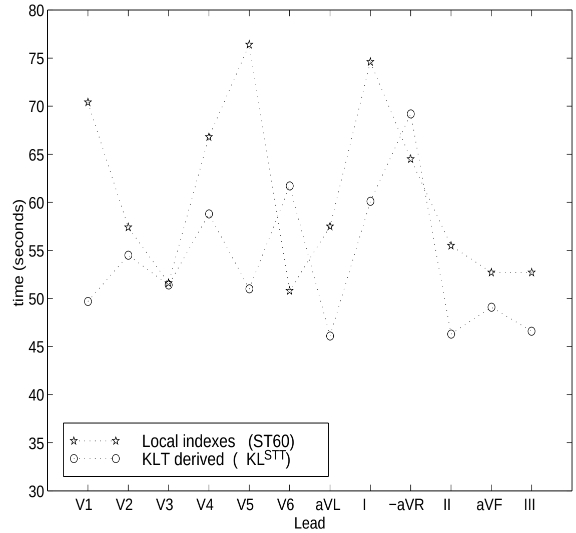
(a) $mean(|ICS|)$ for traditional indexes.

(b) $mean(|ICS|)$ for KLT-derived indexes.

Figure 4: *Mean of the ICS ($mean(|ICS|)$) for the different indexes at the end of the occlusion.*

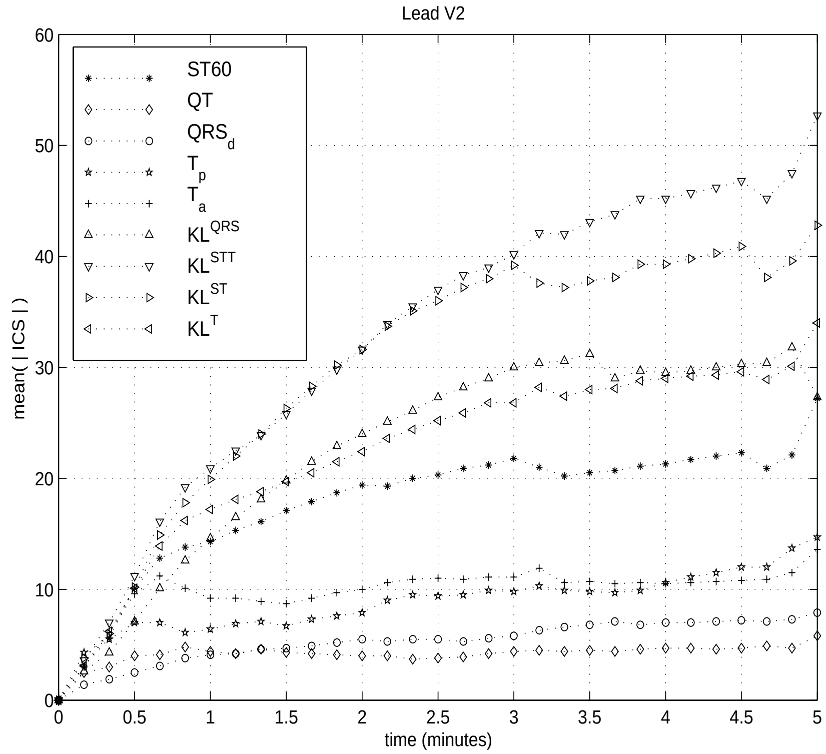


(a) Number of patients that exceeded the threshold.

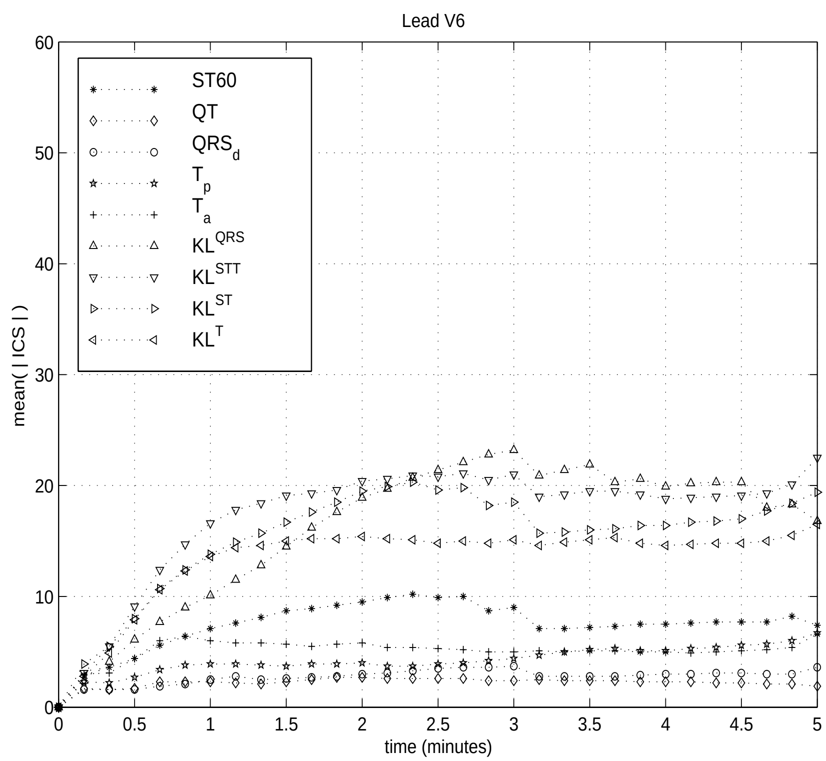


(b) Mean timing of threshold crossing.

Figure 5: *The number of patients in which the threshold was crossed by the* ICS *and the mean timing when was crossed are represented for the different leads.*

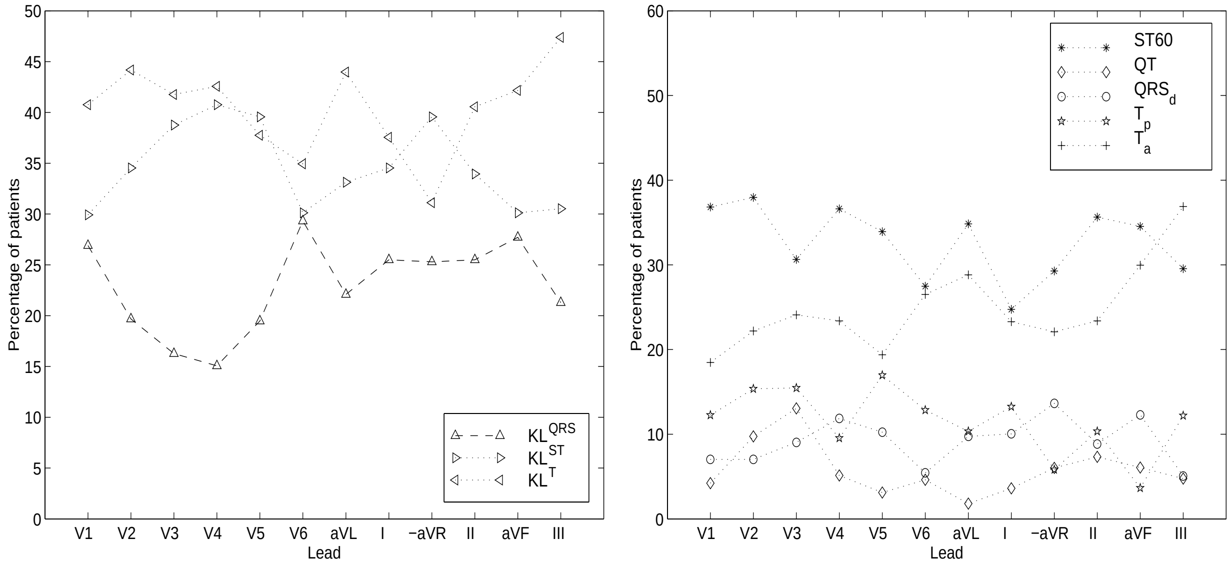


(a) Lead V2.



(b) Lead V6.

Figure 6: *Mean among patients of the different ICS evolution during five minutes of occlusion. Note that different number of patients were averaged due to the differences in occlusion time.*



(a) KLT-derived indexes.

(b) Traditional indexes.

Figure 7: *Percentage of patients in which the different indexes were earlier activated by the ischemic induced changes.*

List of Tables

Table 1: *Summary list of indexes.*

Traditional Indexes	
$ST60$	ST level measured at 60ms after J point
T_a	T wave maximum amplitude
T_p	T wave maximum position with respect to R wave
QT	QT interval duration
QRS_d	QRS complex duration
KLT-derived Indexes	
KL_i^{QRS}	ith order KLT index for the QRS complex
KL_i^{ST}	ith order KLT index for the ST segment
KL_i^{T}	ith order KLT index for the T wave
KL_i^{STT}	ith order KLT index for the ST-T complex
KL^{int}	KLT index with largest ICS among the four first order KLT indexes KL_i^{int} (i=0, ..., 3) for the interval *int*